

# Profiling tropospheric winds with the Goddard Lidar Observatory for Winds (GLOW)

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## ABSTRACT

The Goddard Lidar Observatory for Winds (GLOW) is a mobile direct detection Doppler lidar system designed to measure wind profiles from the surface into the lower stratosphere. Recently, the GLOW lidar has participated in several field deployments measuring tropospheric winds in a variety of conditions including both daytime and night operation. More than 50 hours of line-of-sight wind profile data were obtained in September, 2000 during a three week intercomparison experiment at the GroundWinds facility in North Glen, NH. Typical clear air lidar wind profiles extended to altitudes of 20 km with a 1 km vertical resolution and 1 minute averaging. An additional 40 hours of lidar profiles of wind speed and direction were obtained during HARGLO-2, an intercomparison experiment held at Wallops Flight Facility, VA in November, 2001. A description of the mobile system is presented along with the examples of validated lidar wind profiles obtained during these experiments.

## 1. Introduction

NASA Goddard has been actively involved in the development of direct detection Doppler lidar methods and technologies to meet the broad range of wind observing needs of the atmospheric science community. Applications include spaceborne observation of global winds<sup>1</sup> and ground and airborne measurements of winds for investigation of mesoscale dynamics and atmospheric processes. The Goddard Lidar Observatory for Winds (GLOW) is a mobile wind lidar system utilizing direct detection Doppler lidar techniques for measuring the wind. GLOW is intended to be used as a field deployable system for studying atmospheric dynamics and transport and can also serve as a testbed to evaluate candidate technologies developed for use in future spaceborne systems.

The Doppler lidar receiver in the GLOW lidar system is based on the double edge technique<sup>2, 3, 4, 5</sup>. The double edge method utilizes two high spectral resolution optical filters located symmetrically about the outgoing laser frequency. The details of the double edge method have been recently reported for lidar systems measuring the Doppler shift from either aerosol<sup>6, 7</sup> or molecular<sup>4, 8</sup> backscattered signals. The edge technique is an example of a class of direct detection Doppler methods that are related by the common technologies employed in the measurement. These technologies include the single frequency solid-state laser, high resolution optical filters, high efficiency low noise detectors capable of photon counting and large aperture, non-diffraction limited telescopes. A number of direct detection Doppler wind lidar measurements have been reported<sup>9, 10, 11, 12</sup>.

In this paper we present GLOW lidar wind profiles obtained during several recent field experiments. Examples of lidar results will be given including an analysis of errors and intercomparisons with other wind profiling instruments. The lidar system is described concentrating on the 355 nm molecular Doppler implementation.

## 2. Lidar System Description

The design of the GLOW lidar system is modular to allow incorporation of new technologies (lasers, scanning optics, telescopes, receivers) as they become available. The details of the lidar system design have been described elsewhere<sup>4</sup> and will be briefly summarized here. The laser is mounted on an optical bench that is bolted to the truck frame along with the 45 cm aperture telescope and beam pointing optics. The laser is an injection seeded, flashlamp pumped Nd:YAG laser which has a repetition rate of 10 Hz. The pulse length is 15 ns and the spectral width is 40 MHz at the fundamental wavelength of 1064 nm. Harmonic generation optics produce the 355 nm pulses transmitted to the atmosphere. The maximum laser pulse energy is typically in the range of 70-80 mJ at 355 nm for the molecular Doppler wind measurements. A 45 cm aperture

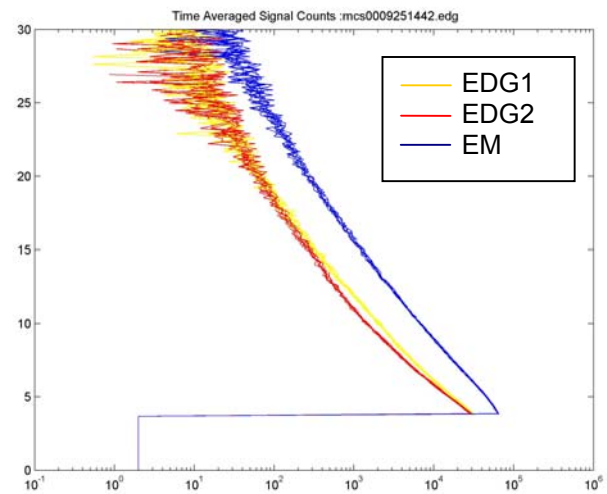
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scanner is mounted on the roof to allow access to the atmosphere. The scanner provides full hemispherical pointing using motor driven azimuth and elevation mirrors. The matching 45 cm, f/2.5 Dall Kirkham telescope is mounted below the scanner to collect the backscattered signal. The backscatter laser light is collected and coupled directly to a fiber optic cable that delivers the signal to the Doppler receiver. The molecular double edge receiver design follows the general principles described recently by Flesia and Korb 1999. It is also similar in concept to the Rayleigh Doppler lidar system described and successfully operated at OHP in France <sup>9, 12</sup>.

In the receiver, the fiber optic from the telescope is coupled to the collimator to produce a collimated beam of 35 mm diameter. This beam is split by beamsplitters into a total of five channels, three of these are directed along parallel paths through a Fabry-Perot etalon filter. Two of these etalon channels (the 'edge' channels) have PMTs operating in photon counting mode. The third etalon channel is used as a reference and uses a PMT operated in current or analog mode. The other two channels serve as energy monitor channels, one has a photon counting PMT and the other has an analog mode PMT. The energy monitor channels provide intensity normalization of the respective etalon channels during calibration.

A capacitively stabilized piezo-electrically tunable Fabry-Perot etalon is used for the high spectral resolution edge filter. The etalon has three sub-apertures each with a diameter of 38 mm. The spectral bandpasses of two of the sub-apertures have been offset from one another and with respect to the third. The magnitude of the offset is defined by a small 'step' coating which has been deposited in two of the apertures on one of the etalon plates prior to deposition of the reflective coating. The two edge filter channels are located symmetrically around the laser frequency in the wings of the thermally broadened molecular spectrum. The reference channel is located such that the outgoing laser frequency appears on the edge of the 'Locking' fringe and is used to make a measurement of the outgoing laser frequency.



**Figure 1 – Photocounts detected in the molecular receiver for the two edge channels, EDG1 and EDG2 and the energy monitor, EM. The range resolution is 250m and 300 shots are averaged.**

The photon counting PMTs provide high detection sensitivity in the upper troposphere and stratosphere where the return signals are small. The analog PMT signals are sampled with a boxcar integrator and the photon counting signals are binned in a multichannel scalar and integrated for a selectable number of shots prior to storage. Typical integration times are 30 seconds (300 shots) to 100 seconds (1000 shots). An example of the signals from the three photon counting channels are shown in Figure 1. The integration time for these signals is 30 seconds (300 shots) and the data are binned with a range resolution of 250 m. These data were obtained during the afternoon of September 25, 2000 as part of the GroundWinds validation experiment. The laser pulse energy for these measurements was 70 mJ. A narrowband interference filter is included in the receiver to restrict the broadband solar background during daytime operation. The 25 mm aperture of this filter is smaller than the receiver design beam diameter of 35 mm. This limited the effective telescope collecting aperture to about 30 cm. The PMT's have been gated off below approximately 5 km altitude to avoid saturation.

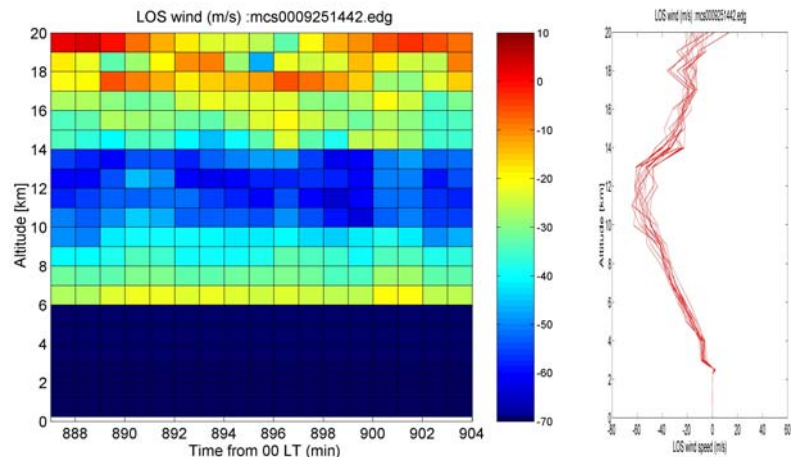
The wind velocity can be uniquely determined by measuring the ratio of the two edge signals. In Figure 1 the magnitude of the two edge channel signals is approximately equal at 5 km and above 20 km. However, there is a significant difference in the two edge signals apparent between 7 and 18 km peaking at around 11 km. This difference in observed signal is a manifestation of the Doppler shift due to the wind as observed through the double edge filters. This will be apparent in the discussion to follow (see figure 2).

### 3. Lidar Observations

The GLOW Doppler lidar began atmospheric operations with the molecular receiver in October, 1999. Following an initial period of testing and calibration we began making wind measurements in early November, 1999. A validation experiment

was held at Goddard that compared the lidar derived wind speed and direction with data obtained from launches of multiple rawinsondes<sup>4</sup>. The first opportunity to test the system in a field deployment was in September 2000 when GLOW participated in the GroundWinds validation campaign held from September 18-29, 2000 at the site of the GroundWinds lidar observatory in North Glen, NH. The experiment included three Doppler lidars, a profiler and GPS rawinsondes launched from the site for intercomparison. A primary objective of the campaign was to operate the lidars in a coordinated fashion with each lidar pointing at common azimuth and elevation angles to produce radial wind profiles which could be intercompared. Each lidar system had somewhat different base spatial and temporal sampling intervals so all lidar profiles were processed to a common spatial and temporal grid to facilitate the intercomparison of the radial wind profiles. The time interval for averaging was 60 seconds and the vertical sampling was 0.25 km for altitudes below 3 km and 1 km for altitudes from 3 to 20 km. Raw GLOW signal data as shown in Figure 1 were processed accordingly to produce sets of consecutive one minute radial wind profiles.

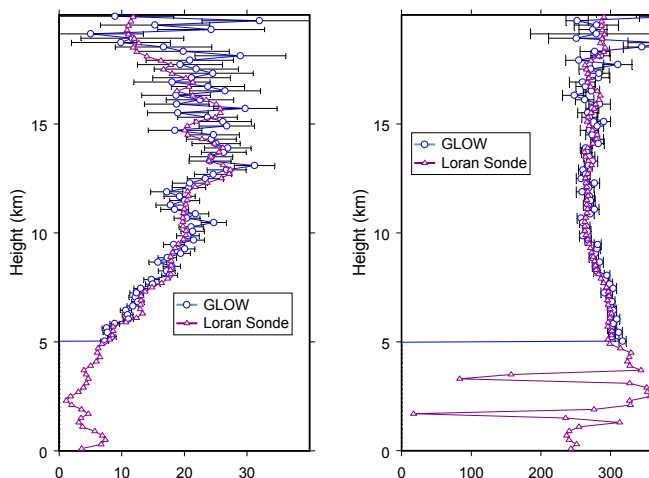
Figure 2a shows the radial wind velocity field measured by GLOW during a 17 minute period on the afternoon of September 25, 2000. The local time is around 14:45 EDT and the lidars were pointed at a 45 deg elevation and an azimuth of 80 degrees. Radial wind velocity is shown as a function of altitude and time (given in elapsed minutes from 00 EDT). An alternate 2-D representation of the 17 lidar profiles is shown in Figure 2b. A strong jet with a peak radial velocity of around 58 m/s (82m/s horizontal wind speed) is clearly observed at 11 km. There



**Figure 2 - a) A color plot of one minute radial wind profiles obtained with the GLOW lidar system on the afternoon of September 25, 2000. b) Same profiles overlaid in a plot of altitude vs velocity.**

is substantial variability in the observed velocity with time. This includes both the random error associated with the instrument and atmospheric variability during the sampling time. Additional examples of the radial wind data obtained from the GroundWinds experiment will be presented including intercomparisons with other instruments.

HARGLO-2 11/15/01 23:49Z



**Figure 3 – GLOW lidar profiles of wind speed and direction from November 15, 2001. Rawinsonde wind profiles are also shown for comparison.**

vertical resolution of 200 m and 10 scan cycles (30 minutes total time; 5 minutes in each direction) are integrated to produce

More recently GLOW participated in the HARGLO-2 validation experiment held Nov 16-20,2001 at the NASA Wallops Flight Facility in Virginia. GLOW was co-located with the HARLIE, a conical scanning aerosol backscatter lidar. The goal of the experiment was to intercompare Doppler wind profiles obtained with GLOW with wind measurements obtained from temporal analysis of the motion of correlated cloud and aerosol structures observed in the HARLIE scans. In addition to the two lidar regular rawinsonde launches provided independent validation. In this experiment GLOW was operated in a step stare scanning mode, taking 30 sec integrations along the four cardinal directions in the sequence N,S,W,E at a fixed elevation angle of 45 degrees. A final zenith pointing 30 sec measurement was made before repeating the cycle. The radial wind profiles along each of the azimuth directions can be derived as was done for the GropundWinds experiment. In addition, the horizontal wind components can be determined from the four line-of-sight profiles. Figure 3 is an example of a lidar profile of wind speed and direction obtained on November 15, 2001 at 23:49UT. The lidar profile has a

the wind speed and direction profile. A rawinsonde launched at 23:00UT is shown for comparison. During the HARGLO-2 experiment over 40 hours of wind observations were obtained with the GLOW lidar during 4 days of operations. Additional examples of lidar data from HARGLO-2 will be presented including analysis of the data using various temporal and spatial averaging schemes, error analysis and intercomparisons with other instruments.

## 5. Summary

A mobile ground based Doppler lidar using direct detection techniques is described. The lidar has been used to obtain profiles of wind speed and direction in the free troposphere and stratosphere to altitudes as high as 35 km. The system was deployed in field for the first time to participate in validation and intercomparison experiments held at the GroundWinds Observatory in the fall of 2000. Over 50 hours of radial wind data were obtained using the GLOW system during the 10 day experiment. Initial comparisons of the GLOW radial winds with the winds from rawinsondes show good agreement. The GLOW data are also being compared with the lidar profiles obtained with the GroundWinds direct detection lidar and the MiniMOPA coherent Doppler lidar as well as with the radar profiler. In November, 2001 GLOW was used to obtain an additional 40 hours of lidar profiles of wind speed and direction during HARGLO-2, an intercomparison experiment held at Wallops Flight Facility, VA.

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## References

- <sup>1</sup> Baker, W., G. D. Emmitt, F. Robertson, R. Atlas, J. Molinari, D. Bowdle, J. Paegle, R. M. Hardesty, R. Menzies, T. Krishnamurti, R. Brown, M.J. Post, J. Anderson, A. Lorenc and J. McElroy, "Lidar-Measured Winds from Space: A Key Component for Weather and Climate Prediction", *Bull. Amer. Meteor. Soc.*, **76**:869-888, 1995.
- <sup>2</sup> Korb, C.L., B. Gentry and C.Y. Weng, "Edge Technique Theory and Application to the Measurement of Atmospheric Winds", *Appl. Opt.*, **31**:4202-4213, 1992.
- <sup>3</sup> Gentry, B. and C. L. Korb, "Edge technique for high accuracy Doppler velocimetry", *Appl. Opt.*, **33**, 5770-5777, 1994.
- <sup>4</sup> Korb, C.L., B.M. Gentry and S.X. Li, "Edge Technique Wind Measurements with High Vertical Resolution", *Appl. Opt.*, **36**:5976-5983, 1997.
- <sup>5</sup> Gentry, B., H Chen and S. X. Li, "Wind Measurements with a 355 nm Molecular Doppler Lidar", *Optics Letters*, **25**, 1231-1233, 2000.
- <sup>6</sup> Korb, C.L., B.M. Gentry, S.X. Li and C. Flesia, "Theory of the Double Edge Technique for Doppler lidar wind measurement", *Appl. Opt.*, **37**, 3097-3104, 1998.
- <sup>7</sup> Gentry, B., S. Li, C.L. Korb, S. Mathur and H. Chen, (1998a) "Lidar Measurements of Tropospheric Wind Profiles with the Double Edge Technique", *Proc. of the 19th ILRC*, Annapolis, MD, NASA CP-1998-207671: 587-590.
- <sup>8</sup> Flesia, C. and C. Korb, (1999), "Theory of the double-edge molecular technique for Doppler lidar wind measurement", *Appl. Opt.*, **38**, 432-440.
- <sup>9</sup> Chanin, M. L., A. Garnier, A. Hauchecorne, J. Porteneuve, "A Doppler lidar for measuring winds in the middle atmosphere", *Geophys. Res. Lett.*, **16**, 1273-1276, 1989.
- <sup>10</sup> McGill, M. J., W.R. Skinner and T.D. Irgang, "Validation of wind profiles measured using incoherent Doppler lidar", *Appl. Opt.*, **36**:1928-1939, 1997.
- <sup>11</sup> Friedman, J. S., C. Tepley, P. Castleberg and H. Roe, "Middle-atmosphere Doppler lidar using a iodine-vapor edge filter", *Opt. Lett.*, **22**, 1648-1650, 1997.
- <sup>12</sup> Souprayen, C., A. Garnier, A. Hertzog, A. Hauchecorne and J. Porteneuve, "Rayleigh-Mie Doppler wind lidar for atmospheric measurements. I. Instrumental setup, validation and first climatological results", *Appl. Opt.*, **38**:2410-2421, 1999.